


Weather Observations Reach the Summit of Mount Everest

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ABSTRACT: The predictability of the weather on Mount Everest's upper slopes can be a matter of life or death for those trying to climb the world's highest mountain, yet the performance of forecasts has been almost unknown due to a lack of surface observations. The extent to which climate change may be affecting this iconic location is also uncertain for the same reason. To address this data limitation, the National Geographic and Rolex Perpetual Planet Expedition installed the world's highest weather station network (reaching within 420 m of the summit) on the Nepal side of Mount Everest in 2019. Its observations have already generated considerable advances in understanding the meteorological environment on the mountain's upper slopes, but the network was compromised by damage to the highest stations in recent years. Here, we describe the expedition that upgraded the network and took it to new heights, focusing on the installation at the Bishop Rock (8,810 m MSL), just below the summit. Almost 70 years after Everest was first climbed successfully, we can now provide open access data to illuminate conditions at Earth's highest climate frontier.

KEYWORDS: Atmosphere; Asia; Automatic weather stations; Forecasting; Mountain meteorology

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Rising to 8,849 m above mean sea level (MSL), the upper slopes of Mount Everest experience barometric pressure around one-third of sea level, strong winds, and air temperatures low enough to freeze exposed skin within a few minutes (Matthews et al. 2020a; Moore and Semple 2011). Such conditions mean that margins of safety are often fine and deterioration in the weather can have severe consequences. Indeed, it is estimated that bad weather contributes to 25% of the deaths on the mountain (Firth et al. 2008), including perhaps the infamous disappearance of Mallory and Irvine (Moore et al. 2010) and during the deadly 1996 “into thin air” disaster (Moore and Semple 2006). While the extreme nature of Mount Everest’s weather is well known anecdotally, detailed scientific understanding of its climate has been lacking due to few weather observations gathered from the upper slopes (Matthews et al. 2020b). Beyond mountaineering safety, this limited understanding of the current conditions translates to large uncertainty in the consequences of climate change for the highest reaches of the Himalayan “water tower,” so called because of the region’s importance as a water source to help sustain downstream demand (Immerzeel et al. 2019).

To both improve climber safety and enhance understanding of water resources, an international team of scientists and Sherpa installed the world’s highest weather station network on the southern flanks of Mount Everest during the 2019 National Geographic and Rolex Perpetual Planet Expedition, as detailed in Matthews et al. (2020b). With five stations between 3,840 m MSL (Phortse) and 8,430 m MSL (the “Balcony”), this network has already generated numerous discoveries, including the identification of remarkable day-to-day variability in oxygen availability that underlines the importance of a well-selected summit window for climbers (Matthews et al. 2020a) and revealing the very high levels of insolation on the upper slopes—enough to drive surface melting at air temperatures well below 0°C (Matthews et al. 2020b) and resulting in an extreme sensitivity to surface albedo (Potocki et al. 2022). Additionally, the network has helped quantify gradients in air temperature and humidity (Khadka et al. 2021), while the use of air mass tracking techniques alongside precipitation observations from the lower stations has provided insights to the provenance of precipitation nourishing the Khumbu Glacier (Perry et al. 2020). Both contributions enhance understanding of regional glacier sensitivity to climate change, which in turn is relevant for quantifying potential future freshwater availability downstream.

Reaching new heights

The 8,430 m MSL Balcony was not originally intended to be the site of the highest station. Instead, this choice reflected the severely limited options for acceptable locations (stations

require relatively flat areas, near the standard climbing route but not in the way of climbers, and anchored into bedrock, which is often covered by snow and ice) as well as the logistical challenges of a very congested summit night in 2019 (Matthews et al. 2020b). Tantalizing questions remained from leaving the upper ~420 m unmonitored: What is the mass balance of the summit snowcap and how might this (and the height of Mount Everest) change as the climate warms? How well are the critical summit-ridge winds captured by weather forecasts? With the demise of the Balcony weather station in January 2020, the upper ~900 m of Mount Everest was once again unmonitored. Wind measurements from the second highest (South Col; 7,945 m MSL) weather station ceased around the same time. Therefore, a decision was made to undertake a maintenance expedition to repair the latter and *replace* the former, ideally at an even higher site, to help resolve these unanswered questions about the weather near the summit.

The *Return to Everest* expedition was launched in partnership with the Department of Hydrology and Meteorology (Government of Nepal), Department of National Parks and Wildlife Conservation (Government of Nepal), and Tribhuvan University in April 2022, following 2 years of delay due to the COVID-19 global pandemic. During the expedition, we learned that a Chinese expedition was installing weather stations on the north side of the mountain, reaching very close to the summit, at a height of either 8,800 m MSL (Rui 2022) or 8,830 m MSL (India Today 2022), depending on reports. We congratulate them on this remarkable accomplishment and highlight that simultaneous observations from altitudinal transects on either side of the mountain may offer rich insights into mountain meteorology. The Chinese team installed stations based on our 2019 design (Matthews et al. 2020b), whereas we updated the choice of wind sensors because of the high failure rate for the model deployed at the South Col and Balcony in 2019, with all (four) being destroyed by strong winds during their first winter. Our new design for the 2022 expedition featured three *different* sensors for redundancy: a special polycarbonate R. M. Young 05108 Alpine anemometer, a Richards C5C stainless steel three-cup anemometer, and an experimental pitot tube built by the Mount Washington Observatory. These were to be added to the South Col weather station (Fig. 1), and to the system intended as a replacement for the Balcony station. Note that the continuity of wind observations from the three lower stations meant that there was no need to make similar replacements at these other sites.

We focus now on our efforts to restore measurements from above the South Col on Mount Everest. Arriving in Base Camp (5,300 m MSL) on 13 April 2022, our team prepared in the usual way for a summit attempt, completing one rotation through the higher camps in between rest periods. The Camp 2 weather station (6,464 m MSL) was also inspected during this acclimatization effort and found to be in good working order, requiring only the net radiometer to be releveled. In an effort to guard against being caught in another crowded summit night, the team was ready for the summit push by 3 May, which was well ahead of other teams. An anxious wait followed in Base Camp as we delayed leaving until the rope-fixing team had closed in on the summit. However, with favorable news of the latter's progress accompanied by a weather forecast indicating light winds (Fig. 2a), we left Base Camp on 6 May aiming to push for the summit on 10 May.

On our first rest day at Camp 2 (7 May), updates from our forecasting team (coauthors Guy and Seimon) gave slight cause for alarm. Winds on 10 May were now forecast to be stronger than previously thought (Fig. 2b). However, the shift was *only* from very favorable to marginal, and combined with news that the ropes were not guaranteed to be in position by May 9, we decided to continue resting and target 10 May. Everything changed, though, on 8 May. That morning's forecast predicted winds could peak at around 24 m s^{-1} on 10 May (Fig. 2c)—conditions that the leadership team agreed would not be suitable for the climb and installation. With supplies at Camp 2 running low, we decided to leave immediately in an attempt to make

the 9 May weather window before it closed. These circumstances were not ideal because the ascent would now require a rapid ~1,500 m climb straight to Camp 4 (the South Col, 7,945 m MSL), where there would be very little time to recover before leaving for the summit. Spurred on by coauthor Perry (expedition lead), the team pushed hard to arrive by 1415 UTC [2000 Nepal standard time (NPT)] 8 May, enabling just a few hours rest before departing again at ~1915 UTC (0100 NPT) 9 May.

The ascent from Camp 4 proceeded well with 13 Sherpa leading scientists Khadka and Matthews as they made good time climbing, despite carrying an extra 60 kg in unassembled parts for the replacement high station. However, upon rounding the South Summit (8,749 m MSL) to gain the exposed summit ridge, it became clear that winds were stronger than the forecast guidance. Nevertheless, at ~0300 UTC (0900 NPT) the team reached the target site (Bishop Rock: 8,810 m MSL, surveyed at this height by coauthor Athans during a 1999 National Geographic survey) and the elite Sherpa team led by Tenzing Gyalzen pursued the installation despite the very difficult circumstances brought on by the weather conditions and physical fatigue. Their success (Fig. 3) was built upon years of training in high-altitude mountaineering and for some of the team, experience of working with the network since its installation in 2019. The first observations from this summit station indicate that the wind chill temperature must have been close to -40°C (with a corresponding facial frostbite time of less than 10 min) while the station was being installed (Fig. 4). These conditions were endured for almost 3 h (the installation was completed at ~0615 UTC/1200 NPT), yet the only (minor) frostbite sustained was to the fingers of scientist Matthews, whose hands were covered far more than those of the Sherpa performing the vast majority of the installation. The Sherpa indeed demonstrated a remarkable ability to perform fine dexterous work without gloves, despite prolonged exposure to the significant cold hazard.

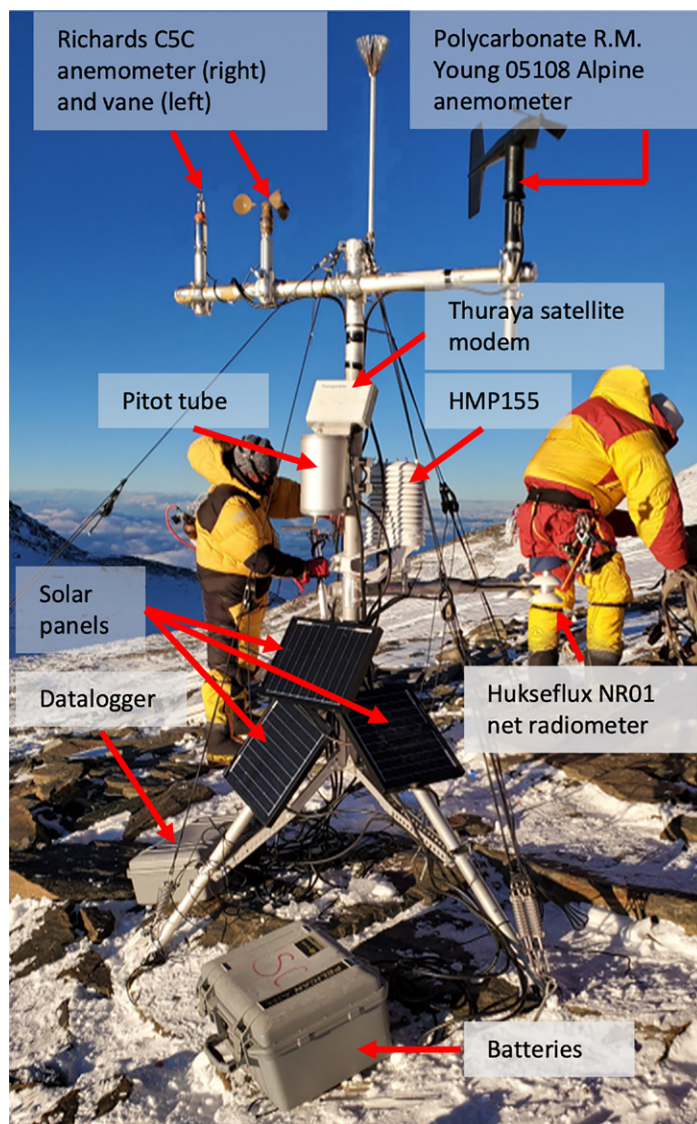


Fig. 1. Tenzing Gyalzen Sherpa (right) and Mingma Nuru Sherpa (left) work on upgrading the South Col automatic weather station at 7,945 m MSL. In addition to the wind sensors mentioned in the text, note that the HMP155 measures temperature and relative humidity and the Hukseflux net radiometer measures incoming and outgoing short- and longwave radiation. A (Vaisala PTB210) barometer is also located in the datalogger enclosure. All data are sent in near-real time via the Thuraya satellite modem, with up to 13 transmissions per day. See Matthews et al. (2020b) for further details of the station design.

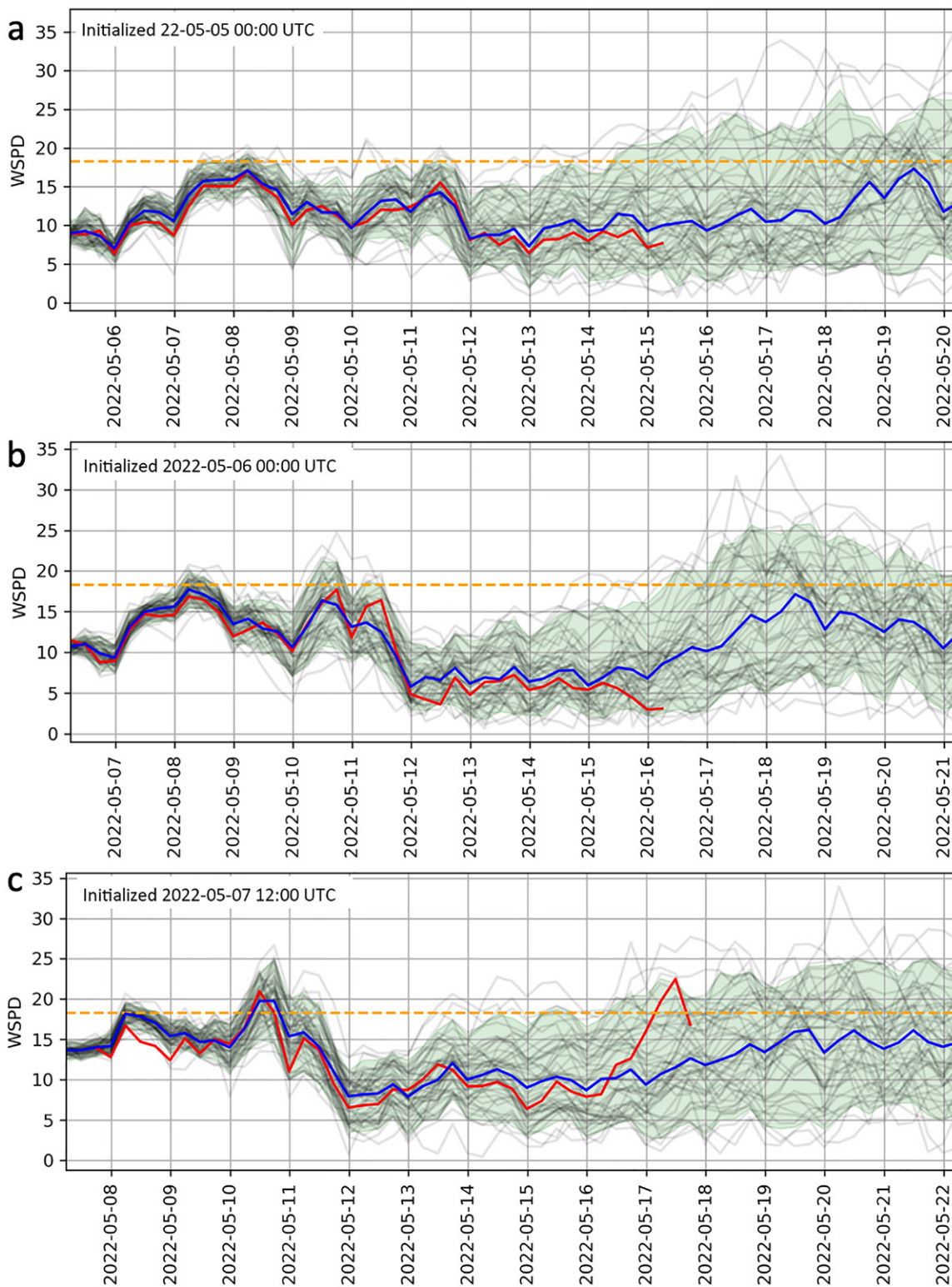


Fig. 2. The original European Centre for Medium-Range Weather Forecasts (ECMWF) forecast plots used on the mountain (received via WhatsApp by the Base Camp team). All forecasts were interpolated from pressure levels to the latitude, longitude, and height of Mount Everest's summit. Initialization dates for the forecast runs are annotated top left of each panel. Note that green shading spans the 5th–95th percentiles of the ensemble, blue is the ensemble mean, and red is the deterministic forecast. The orange dashed line was the authors' best estimate of a safe climbing threshold. Note that the units of all wind speeds are m s^{-1} .

After safely returning to Camp 4 (~0815 UTC, 1400 NPT), most of the team continued to maintain the nearby South Col weather station, completing the upgrade by ~1245 UTC (1830 NPT). Both stations were therefore operational to record the hurricane-force gusts

(reaching 36 m s^{-1} at the Bishop Rock) when the winds strengthened as forecast on 10 May (Fig. 4). This acceleration was consistent with a steepening of the upper-troposphere pressure gradient in the vicinity of Mount Everest, which was likely driven in part by warm-air advection on the eastern flank of Cyclone Asani (Fig. 5). The strong winds presented some difficulty for our safe exit from Camp 4 during the morning, but all were able to descend without incident. Meanwhile at the summit, facial frostbite time fell to less than 2 min as the wind chill plunged to almost -50°C (Fig. 4).



Fig. 3. Lead Sherpa (Sirdar) Tenzing Gyalzen (right) and Kami Temba Sherpa (left) put the finishing touches to the Bishop Rock weather station (8,810 m MSL). View is to the southwest, with the peak of Mount Lhotse (8,516 m MSL) visible in the background.

Learning new lessons

Such a severe cold hazard during the main spring climbing season highlights the importance of a well-chosen summit window. However, the surprisingly strong winds encountered earlier by our team when installing the Bishop Rock station on 9 May underscores

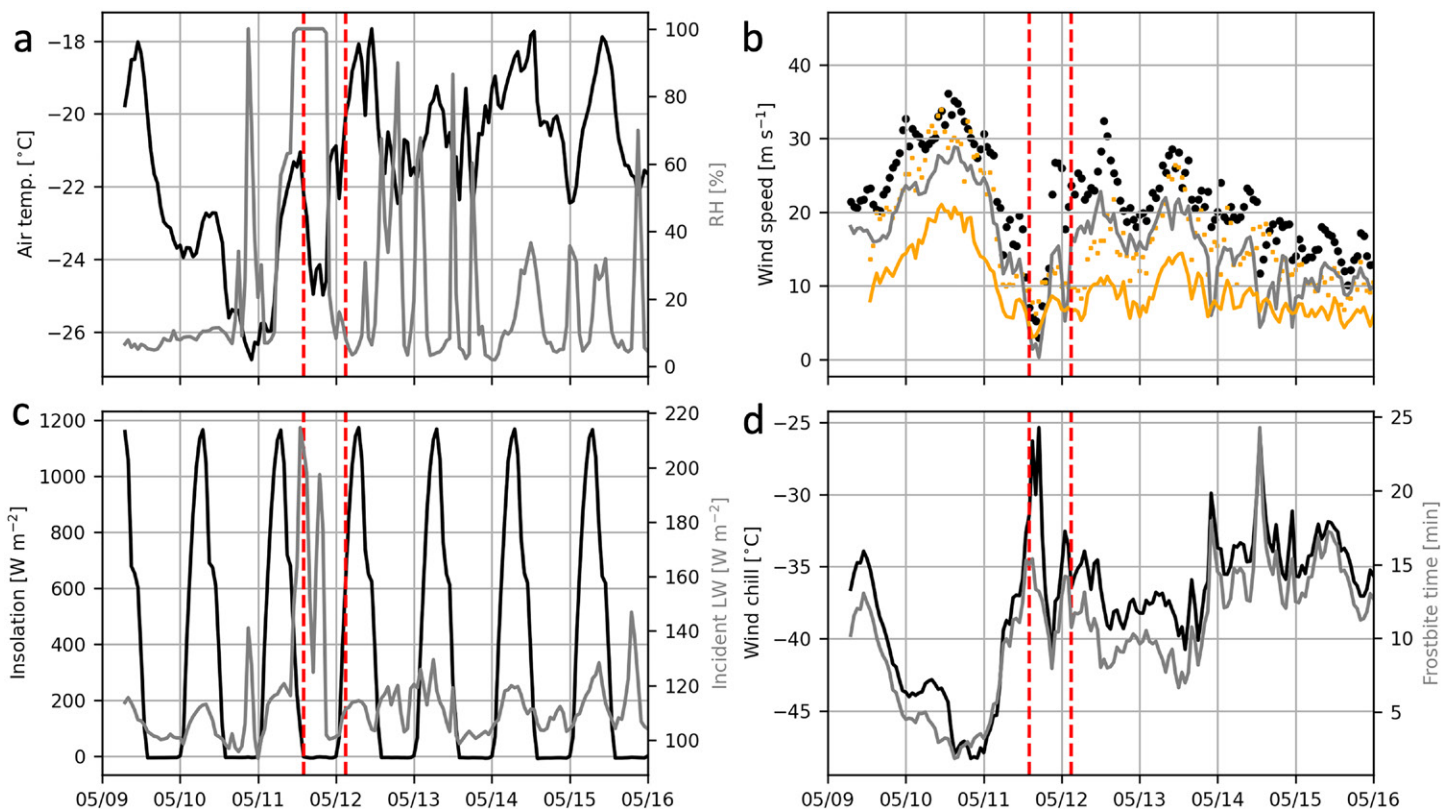


Fig. 4. The first week of observations from the Bishop Rock weather station (8,810 m MSL). (a) Air temperature (black) and relative humidity (RH; gray); (b) hourly mean wind speed (gray), maximum (3-s) gust (black circles), and South Col station (7,945 m MSL) average winds (orange lines) and maximum gusts (orange circles); (c) incident shortwave radiation (insolation; black) and incident longwave radiation (LW; gray); (d) wind chill temperature (black) and facial frostbite time (gray). The dashed red lines demarcate the approximate time that the Full Circle team summited Mount Everest. Note that all dates are UTC.

2022-05-09 00:00 UTC

2022-05-10 06:00 UTC

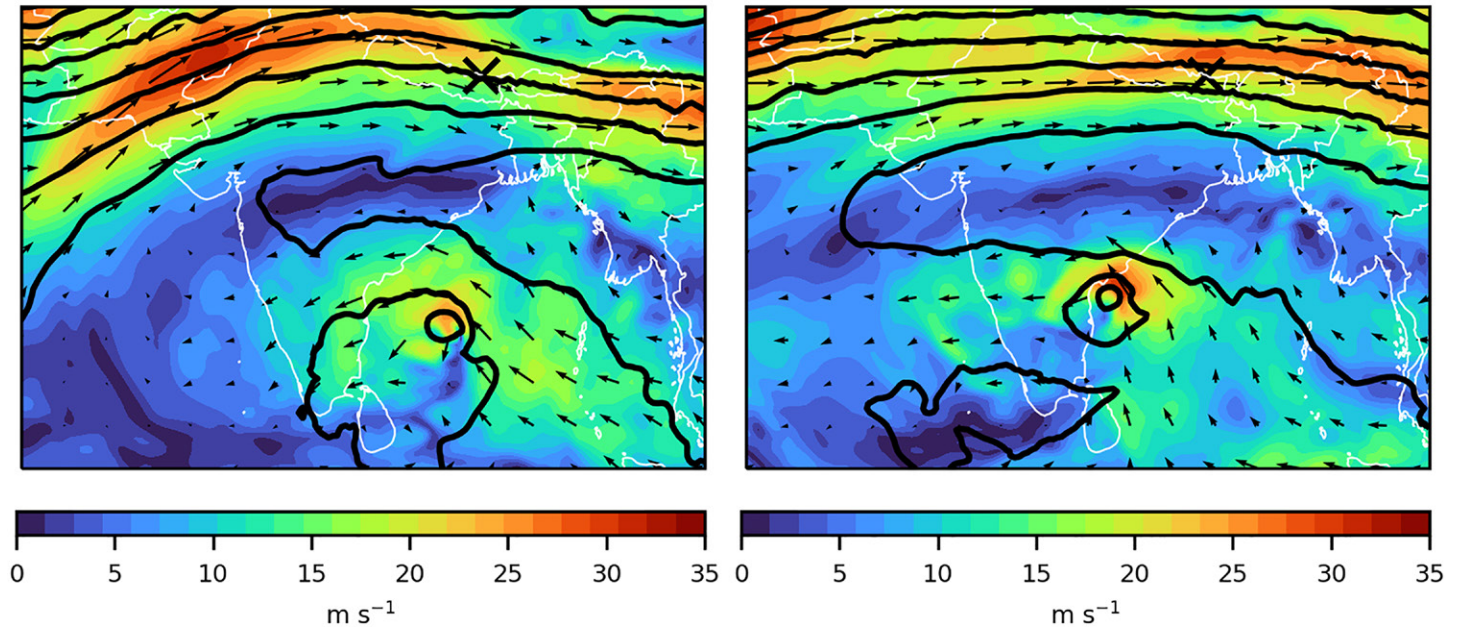


Fig. 5. Wind speeds (shading) and geopotential height (black lines) on the 300-hPa surface from the European Centre for Medium-Range Weather Forecasts ERA5 dataset for (left) 0000 UTC (0545 NPT) 9 May and (right) 0600 UTC (1145 NPT) 10 May. Wind direction and magnitude is also indicated by the vectors. Note that the position of Mount Everest is marked by the black cross, and the cyclonic feature off the southeast coast of India is Cyclone Asani.

that there is still considerable potential to improve weather forecasts on the mountain (Matthews et al. 2020b). Fortunately, the forecasts from the European Centre for Medium-Range Weather Forecasts we used *did* predict the generally favorable weather window on 12 May (Fig. 4), during which the first all-Black (“Full Circle”) team to climb Mount Everest made their successful and historic summit attempt. Since our teams were adjacent in Base Camp and shared several personal and professional connections, we collaborated closely and were honored to share this forecast to help identify the timing of the summit push.

Beyond these insights relevant to mountaineering safety, initial observations from Bishop Rock help our understanding of the hydrological cycle at the top of the Himalayan water tower. With insolation reaching close to $1,200 \text{ W m}^{-2}$, relative humidity falling below 2%, and winds exceeding 30 m s^{-1} (Fig. 4), we anticipate that relatively high sublimation rates are possible. This is because very steep near-surface gradients in vapor pressure should be expected as the surface is radiatively heated relative to an atmosphere so far from saturation, and the strong winds would enhance vapor transport along this gradient. We therefore anticipate that summit sublimation rates are least comparable to the South Col, where they can exceed $120 \text{ mm water equivalent a}^{-1}$ (Potocki et al. 2022). For snowpacks to be in balance, input must match this rate of loss, suggesting precipitation may be much greater on the upper slopes of Mount Everest than would be inferred by extrapolating measurements from lower elevations (Salerno et al. 2015). A local but highly symbolic consequence of such a high mass turnover is that appreciable interannual variability (perhaps exceeding 100 mm) may be possible in the thickness of the summit snowpack and therefore the height of Mount Everest. At larger scales, our new observations should enhance understanding of the processes determining the mass balance of high-altitude snow and ice stores in the Himalaya, potentially leading to refinements in models and improving projections of potential future freshwater availability downstream.

Conclusions

As the highest peak on Earth, Mount Everest is an alluring but potentially deadly challenge for hundreds of climbers each year. Extreme weather on the upper slopes is a major part of

this threat, not least because the performance of weather forecasts there is mostly unknown due to a lack of in situ weather observations. The absence of weather monitoring on the upper reaches of Mount Everest has also limited understanding of how its vast stores of frozen water are likely to respond to climate change. In turn, this reflects broader shortfalls in our knowledge of the future of the Himalayan water tower. Motivated by these gaps in understanding, the 2019 National Geographic and Rolex Perpetual Planet Expedition installed the world's highest weather station network on Everest. Here we outlined critical upgrades to this array, focusing on the replacement of the highest station with an installation at the Bishop Rock (8,810 m MSL). In telling the story of this expedition, and exploring the initial data from the new station, we highlighted the potential for these data to improve weather forecasts and climber safety. We also emphasized their utility for helping to understand and quantify the processes controlling the amount of snow and ice stored on the mountain, which is relevant more broadly for understanding the future of freshwater availability downstream of such Himalayan peaks.

Other researchers are also strongly encouraged to make the most of these data in studying an environment that has, for almost 70 years since the first summit (in 1953), been a site of global significance, yet unmonitored due to profound logistical challenges. That these difficulties were overcome speaks to the remarkable ability of the climbing Sherpa who made it possible (see “Acknowledgments” section). To maximize its utility, data from the Bishop Rock station are freely available to the public, distributed as both a (lightly) quality-controlled archive, and via a low-bandwidth page that should be accessible even for mountaineers experiencing patchy internet connectivity at Mount Everest Base Camp (see “Data availability statement” section). We hope that opening access to the data in these ways will help make climbing Mount Everest safer, and will accelerate scientific understanding of this high-altitude climate frontier in the heart of the Himalayan water tower.

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Data availability statement. The archive of (lightly) quality-controlled data is available at www.nationalgeographic.org/projects/perpetual-planet/everest/weather-data/, and the most recent data can be viewed at the low-bandwidth page: <https://everest-pwa.nationalgeographic.org>. Note, however, that at the time of writing (late August 2022), the Bishop Rock station had stopped transmitting, meaning that the near-real-time data cannot be accessed. Prolonged lapses in transmission during the monsoon are not unprecedented on the upper mountain, so we are hopeful that the data feed from the Bishop Rock will resume. Efforts to revisit the station to bring it back online will be considered if required.

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